Different Charging Topologies for Fast Charging Station of New Generation Electric Vehicles: A Review

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Abstract- *This paper reviews existing topologies which are been used for fast charging stations for charging Battery Electric Vehicle (BEV). Topologies with respect to switching frequency, electromagnetic interference (EMI), output power, component count, losses, effectiveness, reliability, cost and charging time of course. The purpose is to provide low cost and high power density based efficient charging solution, for which a converter having high power factor (nearly unity) low harmonic distortion (THD) in supply current and increased efficiency is required to be connected to grid. There is also a focus on second stage DC-DC converter for vehicle battery charger which is ZVS full bridge DC-DC converter which adjusts the battery parameters. It has been analysed that Interleaved converter, bridgeless converter, modified bridgeless converter and converter with resonant circuit topology has proven to have low input voltage current ripples and improved power factor during EV charging. Also, a minor emphasis is made to integrate charging station with utility grid and renewable energy sources. The analysis done will help the researchers and future automotive engineers to make better choice of converter topology which is to be incorporated for fast charging of EV's*

Keywords- DC-DC converters, fast charging system, battery electric vehicles, improved bridgeless conversion, power factor correction and efficiency

I. INTRODUCTION

Electric vehicles are been on a very rapid development stage due to various environmental concerns like CO_2 emission, greenhouse effect and fossil fuel depletion. For sustainable development transportation segment is orienting towards battery powered electric vehicles (BEV) which is dominating the conventional vehicle structure only because it is eco-friendly in nature. BEV require On board and off board charging with uni-directional and bi-directional power flow, of which unidirectional reduces battery degradation on the other hand bi-directional charging supports power stabilization. On board chargers charge EV from workplace or home they have a significant advantage of high power density and efficiency but with long charging time, whereas Off board chargers are actually the charging station just like gas filling station and its purpose is to charge the vehicle fast. Over few decades research is been carried on fast charging of BEV on the area of power factor correction, lowering total harmonic distortion and charging the battery first at constant current (CC) and thereafter on constant voltage (CV) mode. For the same an improved PQ-based EV chargers, which draws a sinusoidal input current with a high PF, and where the output voltage is regulated stiffly at constant value are required. An off-board configuration offers more practical solution due to reduced vehicle weight and suitability to charge at high power range. Different PFC converter topologies with interleaved input at the front-end and zero-voltage-switching technique are in existence. The interleaving of two phase inputs comes with the benefits of reduced output ripple current and reduced size of the inductor. An LLC resonant converter fed EV charger offers the additional advantage of low electromagnetic Interference (EMI) noise and low switching loss. For a full bridge PFC converter individual grate driver for semiconductor switches has a disadvantage of increased size and complexity. Single stage charger is quite reliable but presence of ripple content in output current requires very high DC link capacitance. Diode Bridge Rectifier (DBR) fed PFC converter affects the charger efficiency due to conduction loss. A Bridgeless PFC converter gives better solution for PQ improvement of EV charger. This paper presents a comprehensive review of different converter topologies i.e front end as well as on battery side used for fast charging of BEV

II CONVERTER AND CHARGING TOPOLOGIES

1. Buck-Boost Converter as a Power Factor Correction Controller

For a battery fed electric vehicle the battery should charge and discharge in a proper manner so that its performance and life is improved, for this a conventional buck-boost converter [2] operating at CCM is used, Buck-boost converter shown in fig.1 operates on DC supply so for this we can convert ac to dc via diode bridge rectifier.

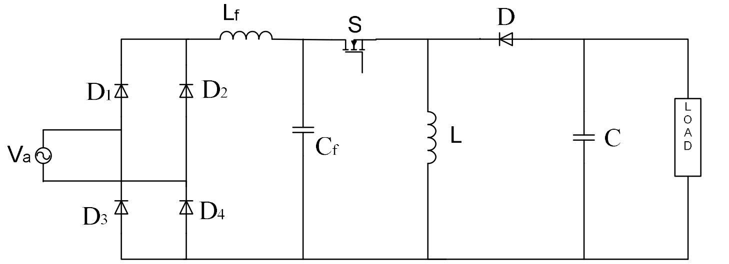

Fig1. Single Phase PFC Buck-Boost Converter

The major problem incurred using a DBR is of poor power factor along with distortion at input side of supply, for this active power factor correction controller known as line frequency current shaping control scheme is been introduced which has constant voltage and constant current control which makes power factor near to unity. Here [1]-[2] output voltage and current of converter is fed to PI controller to get PWM pulse with an adjusted duty cycle and these pulses are given to thyristor switch (MOSFET or IGBT) for the supply current to be sinusoidal and getting unity power factor. This is one of the most simplest topology for high power application.

2. Bridgeless SEPIC Power Factor Correction Controller

The term bridgeless is been introduced which avoids the use of a diode bridge rectifier [3], this topology reduces the component count with low conduction loss. SEPIC converter is been opted for PFC application because of its advantages like continuous input current and isolation. Further it eliminates the use of high end filter requirement and also reduces voltage stress on switches.

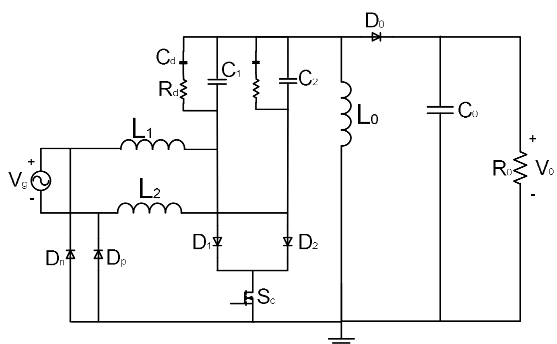

Fig 2. Bridgeless SEPIC Converter

Bridgeless SEPIC converter [4] shown in fig.2 here operates on discontinuous current mode to get natural zero current turn off in output diode and zero current turn on at switches this reduces complexity in control. This topology also has an additional control as in [5] to achieve sinusoidal current even if there is harmonics present in supply voltage, this harmonic if present is detected on source side and the control is directed to voltage follower or average current control this is the first control carried and the other control uses an average current control strategy which is been activated on presence of harmonics in ac line voltage, to get sinusoidal current and maintain unity power factor at source side

3. Landsman Power Factor Correction Converter

Conventional Landsman converter [7] is a buck-boost converter whose output can be boosted or bucked by controlling the duty cycle. The disadvantage is that it does not have high voltage conversion ratio. The first modified version construction consists of thyristor switch, capacitor, diode and inductor (input and output), this is connected to DBR along with a DC bus capacitor shown in fig.3. This converter regulates the DC voltage to 300V and is independent of source and load variations. This regulated voltage is been fed to dual output flyback DC-DC converter for supplying power to load. The flyback converter works on peak current control mode and has an inbuilt protection features. Further modification i.e bridgeless version of Landsman converter [6] is been used which consists of two parallel switches which operates in synchronization in discontinuous mode in respective half cycle of mains voltage to improve the power factor to unity. DCM operation has a benefit of low cost and simple operation of circuit, a voltage follower PI controller is used to regulate the intermediate DC link voltage of charger. A flyback converter on second stage (battery is connected) is controlled using dual loop PI controller, battery charging current is regulated in the range from 60% - 100% of SOC with this PI controller during CC and CV mode. So improved power quality charging of EV battery can be achieved.

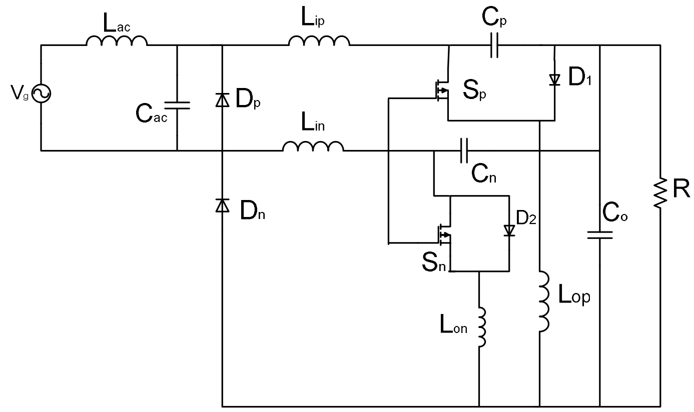

Fig.3 Basic Bridgeless Landsman Converter

4. Resonant DC-DC LLC Converter

LLC converter [8]-[9] operates very close to resonant frequency and it has a higher efficiency over conventional PFC converters, as conventional boost-type power factor correction (PFC) converters are unable to provide ultra-wide DC link voltages due to its dc voltage control. LLC converters have high power density due to ZVS operation. For increasing the power density the frequency can be increased to hundreds of kHz for active power devices like SiC MOSFETS, SiC MOSFETS has many advantages over conventional Si MOSFETS. SiC converters has minimum conductor or component losses and switching losses thus it has a greater efficiency.

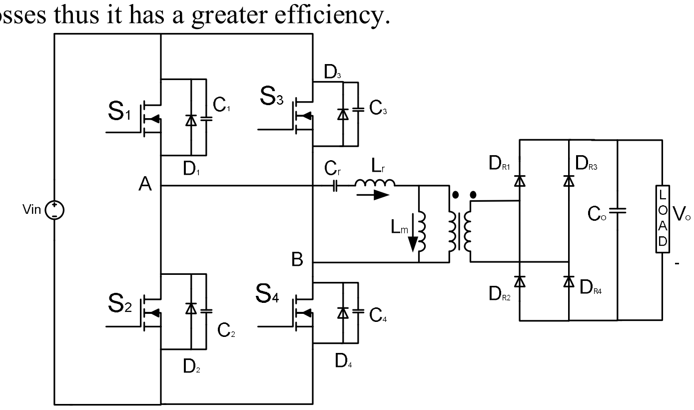

Fig.4. Full Bridge LLC Converter

Fig.4 shows a full bridge LLC converter which consists of four switches, resonant tank, a transformer and a bridge rectifier. The circuit has three passive components on the input side. The secondary side is a bridge rectifier with a capacitive filter. The input side series capacitor provides automated flux balancing. This converter works with two resonant frequency one is due to L_r and C_r and other is due to L_r, L_m with an additional C_r

5. LUO Converter

LUO-converters in fig. 5 are a set of new step boost DC-DC converters [10], which were evolved from models using the technique of voltage lift. These converters perform positive to positive increasing conversion of DC-DC voltage with greater density of power, cheap topology and high efficiency in simple structure.

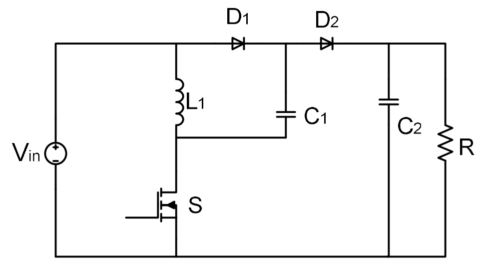

Fig. 5. Basic Circuit of LUO Converter

Bridgeless modification shown in fig 6 of this converter [11] gives high power density and low cost EV charging with a high precision in only a single switching cycle. Input current of the charger gets reduced and it makes source voltage more accurate and high power factor can be achieved. Bridgeless LUO converter can be made by merging multiple LUO PFC converters along with combination of inductors on AC supply side. This converter is been used for high frequency voltage enhancement and it is been supplied bto high frequency transformers, the output of the transformer is given to flyback converter which in turn is connected to battery unit for charging and discharging

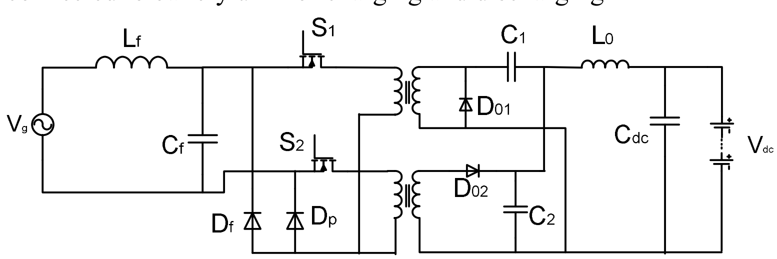

Fig 6. Modified Bridgeless ZETA LUO Converter

6. CUK converter fed resonant LLC converter

In this topology AC CUK converter is been fed by diode bridge rectifier shown in fig 8, here an input filter is is connected to reduce the current and voltage ripples. Output of CUK converter is given to LLC resonant converter [12]-[13] which produces pulsating DC output for linear transformer. Transformer output is given to battery via diode bridge rectifier. Switching pulses are provided in closed loop fashion where system takes battery current and voltage as feedback and is fed to PI controller. CUK converter is operated in DCM mode because of its natural current shaping. This topology eliminates the use of half bridge converter with LLC as in fig 7 which operates at ZVS thus reducing switching losses. Bridgeless topology came into existence due to its increased efficiency and eliminating inrush current issues also switching losses are been nullified

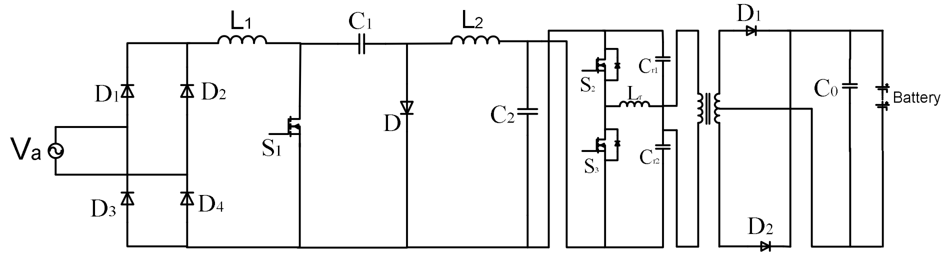

Fig.7. CUK Converter Topology Fed LLC Converter

7. Conventional and Bridgeless CUK converter

Cuk converter have low input current ripple and can operate at wide duty cycle range, this converter also provides continuous output current which is not with SEPIC converter. Cuk converter provides more feasible charging characteristics to battery due to its low ripple in battery current

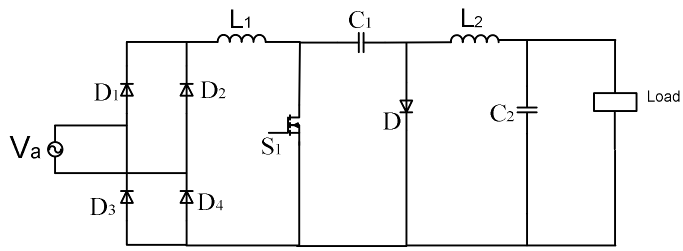

Fig.8 Basic Cuk Converter

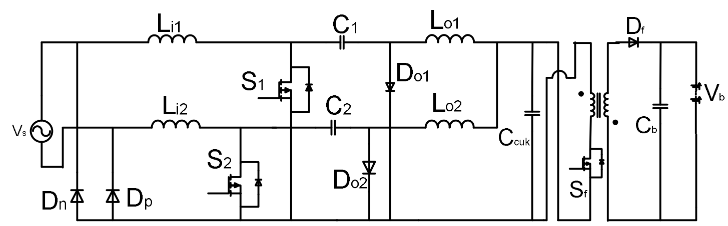

Fig.9 Modified Bridgeless Cuk Converter

An improved bridgeless (BL) Cuk converter (EV) charger [14] with high power factor and increased efficiency offers low cost and high-power-density-based charging. This charger has got less number of devices operating over one switching cycle, which reduces the additional conduction loss which is due to a diode bridge rectifier of a conventional charger. Hence, the charger's efficiency is improved. The additional advantage of the topology is that unwanted capacitive coupling loop is removed, as well as the unwanted conduction through the body diode of the inactive switch is avoided. This also improves the charger's efficiency. For constant current and constant voltage charging, the commands are coordinated by a flyback converter shown in fig 9. This charger draws a sinusoidal current from ac mains and the total harmonic distortion in the supply current is reduced also improved power factor is obtained

8. AC-DC Mode of Charging EV

Indian Government is looking forward for massive electric vehicles on road by 2030, this increasing number of EV will require more charging facility which is Fast Chargers (FCHAR). Li-Ion battery is a primary source in all EV, also an EV may have an additional battery for its auxiliary loads. These loads operate at different voltages for this in [15] development of single converter topology which is Multi-Mode power converter (MMPC) with multifunctional operation on single interleaved converter is been developed.

This integrates AC-DC mode while charging an EV, bidirectional DC-DC mode for auxiliary Battery Management System (BMS) and DC-AC mode for Vehicle to Grid (V2G) operation. This method of charging reduces voltage and current ripple (10% of inductor current in both buck mode and boost mode of operation) also improves power factor during charging. This MMPC consists of MOSFET/IGBT's with anti-parallel diodes as shown in Fig 10

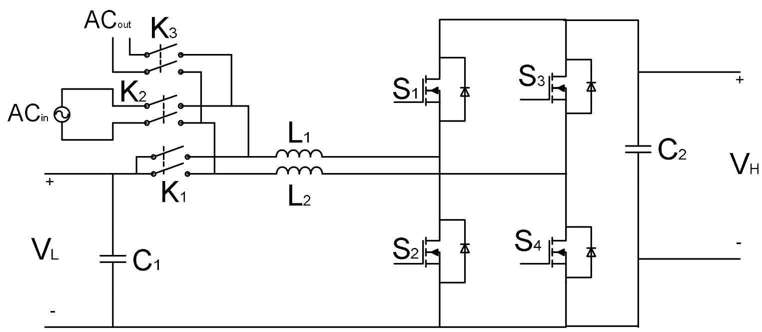

Fig10. MMPC Topology

Selection of different operating modes can be achieved by selecting switches K_1, K_2, K_3. V_L is the low DC voltage at Auxiliary battery side and V_H is the high voltage DC at the primary battery. For bidirectional mode of DC-DC converter switch K_1 is turned ON and other switches are in OPEN position. This model is also with an interleaved topology with a pai tog buck and boost converters. When upper pair of IGBT is acting as a switch and lower pair as diodes its Buck operation and vice versa is Boost operation. For AC – DC converter mode, switch K_1, K_3 are off and K_2 is on. During this mode the main (primary) battery is charged from supply mains, and system works as full bridge rectifier. For DC – AC converter mode K_3 is turned on keeping K_1, K_2 off, energy flows from the battery to grid (V2G operation). Both mode of operation are selected manually by the user.

9. Bi-directional single phase Three- Level Stacked Neutral Point Clamped (3L-SNPC)

Bidirectional single-phase, three-level stacked neutral-point-clamped (3L-SNPC) converter [16] in for EV Charging Station behave as a rectifier or an inverter depending upon direction of flow of power. This topology can be easily extended to a three-phase version. Also, this charging station (utility grid) can be easily integrated with renewable energy sources, which can absorb or inject energy into the ac grid with high power factor and reduced harmonic content of current. The main advantages this bidirectional topology feature is existence of a three-level voltage across each leg and the neutral point, thus filtering requirement are reduced when it is made to compare with typical two-level voltage structures used in EV charging station. The voltage stresses on all semiconductors are equal to half of the total dc-link voltage; power factor is nearly unity in any mode of operation; and the voltages across the dc-link capacitors are balanced.

Previously all the topologies which incorporated Three level Neutral Point Clamped (3L-NPC), three-level [17] active stacked neutral point clamped (3L-ASNPC) had AC-DC power conversion and bidirectional version was not presented, but this topology incorporated this feature too. It also permits charging of independent batteries and even injecting power into the ac grid.

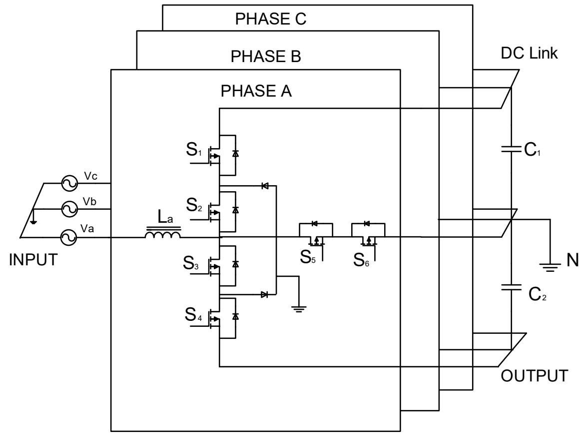

Fig 11. 3-phase Bi-directional 3L-SNPL Converter

This converter has clamping diodes (D_c), active switches (S), respective body diodes (D), storage inductors (L_A), DC link capacitors (C) and three phase voltage source and a dc voltage source that represents the dc link to provide bidirectional power flow as shown in fig 11. Three control loops are required to shape the currents through the inductors, balance the voltages across the capacitors, and regulate the dc-link voltage, resulting in bidirectional power flow and high power factor. In order to provide bidirectional power flow S_5 and S_6 have been added to the converter, which behaves as a bidirectional switch.

DC link is composed of two capacitors C_1 and C_2, two carriers are necessary as represented in fig. 12. In this case, only two switches are allowed to be on at the same time, while others remain off. Switches S_1 and S_2 are only turned on when the modulator is greater than the carrier V_{saw1} during the positive half cycle. Switches S_3 and S_4 will be turned on when the modulator is less than the carrier V_{saw2} during the negative half cycle. Analogously, switches S_5 and S_6 will be driven together when switches S_1 and S_4 are simultaneously off.

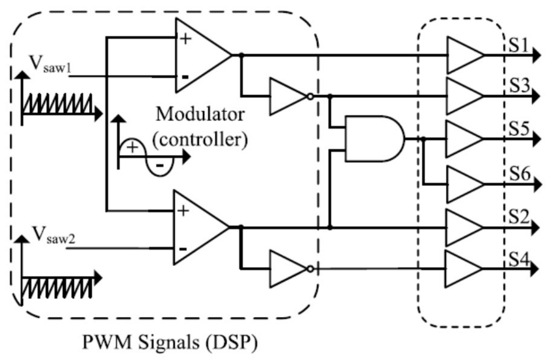

Fig.12 PD-SPWM and generation of the drive signals

10. Isolated Multi-Port Converter

For smart micro-grid, EVs with some distributed energy storage units can be used to supply power to loads during the peak hours which minimizes the effects of power failure in particular area and improve quality of power. To achieve this, an isolated hybrid multi-port converter topology is required [18] which controls and balances power flows in multiple direction i.e among renewable energy sources, EVs, and the grid. This topology is a combination of multiport dual active bridge (DAB)/triple active bridge (TAB) converter, bidirectional dc– dc converter, and dc–dc unidirectional converter. Bidirectional dc–dc converter interface EV battery to achieve bidirectional power flow between utility grid and the energy storages as in fig 13. DC–DC boost converter interface PV module. to achieve bidirectional power flow with the utility grid. A bidirectional AC–DC converter is used to generate sinusoidal current in the grid side for high-quality power conversion. In this topology bidirectional DC-DC converter is interface the energy storage devices, which controls the charging and discharging operation of the storages. The topology can be extended to N different DC buses through a multi-winding transformer (MWT) to handle a variety of dc voltage sources.

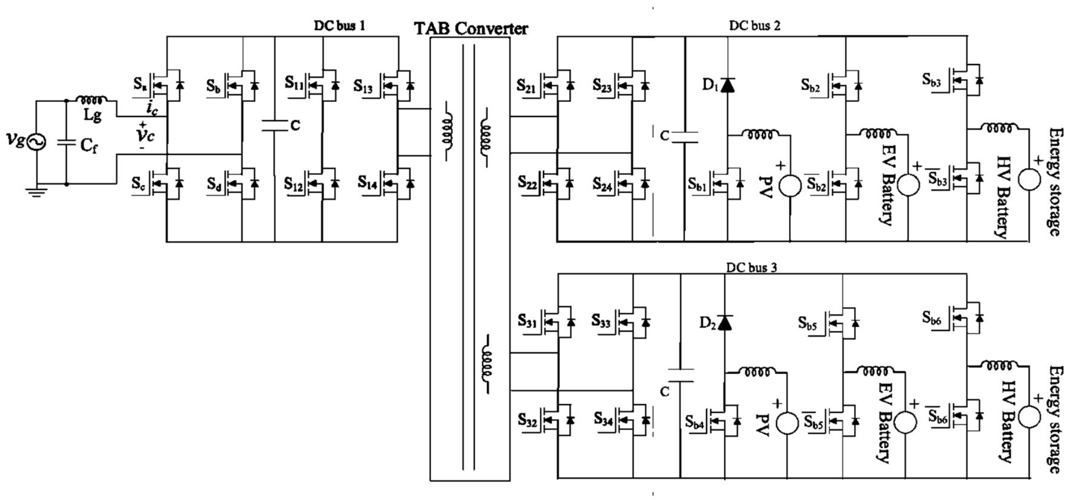

Fig.13 Multiport dual active bridge (DAB)/triple active bridge (TAB) converter

11. Multiphase AC-DC Converter

In this topology the charging station draws a current at low total harmonic distortion and high power factor (PF), without using PF corrector and active/passive filter circuits from grid which meets IEEE-519 PQ standard. This uses 18-phase ac–dc converter for an EV charging station, which consists of three single-phase multiwinding transformers (MWTs) and diode rectifiers [19]. MWTs enables direct conversion of a three-phase utility supply into an 18-phase which reduces the THD in the input line current AC-DC converter operates at line frequency without the need of high frequency active switches. For charging an EV in constant current (CC) and constant voltage (CV) mode, a multiphase (interleaved) dc–dc converter is used.

To reduce THD in the three phase input line current, three-phase voltage supply is converted into a multiphase (18-phase) power supply through three single-phase MWTs this is zig-zag arrangement. The obtained multiphase power supply is connected to the diode bridge AC-DC converter. The diode bridge rectifier converts an 18-phase power supply into DC power and feeds the DC-bus. The use of diodes in AC–DC converter makes charging station robust, reliable, and efficient. A multiphase (interleaved) DC–DC buck converter is used for charging the EV in CC and CV mode.

12. Partial Power Rated DC-DC Converter:

For a very high fast charging of EV which an extreme fast charging station which can charge simultaneously multiple EV, cascaded H-bridge converter is utilized to directly interface with the voltage grid while dual-active-bridge built soft-switched solid-state transformers are used to attain galvanic isolation. Here in [20] a topology where partial power rated DC-DC converter as in fig 14. is used to charge individual EV. This allows independent control of charging of each EV Partial power processing processes only a small power of total battery charging power for this a full bridge phase shift converter is required. This topology has a modular multilevel cascaded H-Bridge (CHB) Front End Converter (FEC) along with solid state transformer (SST) this system has a low voltage dc link which interfaces local DC microgrids

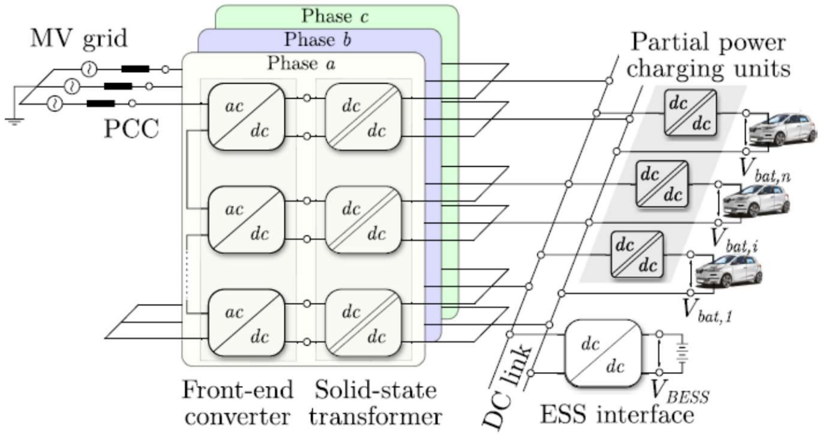

Fig.14 Partial rated charging converters.

DC-DC converter allows partial power processing for each charging unit, these charging units are rated only to handle a fraction of the power required for battery charging. Partial power processing units can reduce the installation and operating cot of extremely fast charging station (XFC) which is about 100,000$ per station cost and simultaneously can improve charging efficiency too.

13. ZVS Tuning Method for Double-Sided LCC Compensated Wireless Power Transfer System

An LCC compensation can be adopted for primary side and a zero current switching (ZCS) can be achieved by tuning parameters of compensation network. The same compensation network when applied in secondary side, can minimize the reactive power and unit power factor can be got. A double-sided LCC compensation network when applied to WPT, its resonant frequency was irrelevant to the coupling coefficient and the load conditions. Also, its tuning method for getting zero voltage switching (ZVS) shows that double-sided LCC compensation [21] topology is less sensitive to the self-inductance variations, lower voltage and current stress and higher efficiency was achieved with respect to SS compensation topology. However, the turn off currents of the primary side switches were relatively large at the low input voltage condition which lowers the efficiency of the system also the relationship between the input voltage and the output power was not linear.

When an additional capacitor was added shown in fig 15. to same compensation topology on secondary side for having ZVS operation of the primary side switches, the resonant frequency of the resonant network was still irrelevant with the coupling coefficient and the load conditions. Meanwhile, the turn off current of the primary-side switches at the low input voltage range was lowered. Consequently, the efficiency of the WPT at the low input voltage range was been improved. The relationship between the input voltage and the output power was more linear than that of existing earlier ZVS tuning method.

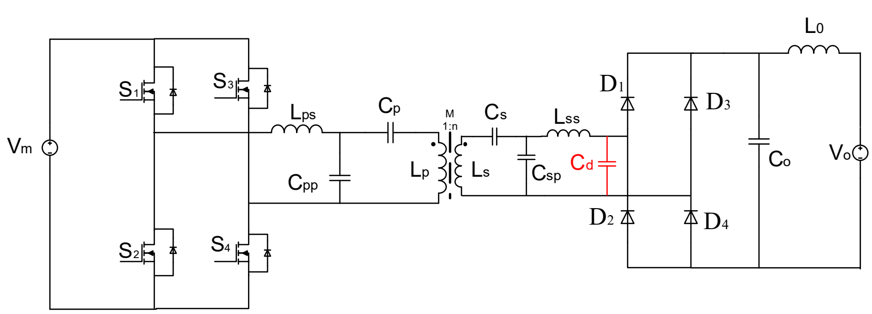

Fig 15. Double-sided inductor/capacitor/capacitor (LCC) compensation topology for wireless power transfer system

14. Three Port DC-DC Converter

Here unidirectional series resonant topology was applied for Fast charging port due to its high efficiency high power density and low electromagnetic interference. Three ports as in [22] are coupled with three winding transformer of which the one port is input port and other two ports are fast charging and slow charging ports. Input port consists of an active full bridge converter connected to a DC source, fast charging port is with a resonant tank and a full bridge rectifier whereas slow charging port is of low power rating and connected to vehicle or batteries. The energy stored via slow charging can be used to support the grid and therefore designed with active full bridge with bidirectional power flow structure. Here the role of Dual Active Bridge (DAB) supports simple bidirectional power flow compared to resonant converter. In this topology phase shift and frequency modulation control methods along with ZVS at all switches are adopted for fast and slow charging ports respectively also optimal phase shift angle control minimised the transformer current when DAB is been required to operate for slow charging.

15. Voltage Balancer with DC-DC Converter

As DC microgrid is gaining popularity so electric vehicle charging station with DC charging unit can perform very well with a good efficiency over AC charging. Bipolar DC bus configuration has an upper hand over unipolar type because it has got two voltage levels which can interface with DC load of different ratings, bipolar DC bus operation comes with asymmetricity which is due to unbalanced power distribution between DC buses this can cause voltage imbalance thus lowering power quality. For this Voltage Balance Control (VBC) [23]-[24] is required and several topologies of voltage balance were introduced of which series-capacitor high conversion ratio (SC-HCR) dc–dc converter was developed which is not affecting the output power which was the major problem with three level (TL) voltage balancer. This topology has got a wide voltage balance range along with high conversion ratio with low voltage and current stresses on switches

16. Vienna Rectifier

Vienna rectifier [25]-[28] is actually a six active semiconductor switch along with six diodes. The voltage stress on each semiconductor switch and diode is half the DC voltage. There are three inductors on AC input along with two capacitors connected parallelly on the DC side. The neutral point of the grid is associated with the neutral point of the DC link. Viena rectifiers are gaining popularity for AC-DC power conversion [26] for electric vehicle charging station because of its low total harmonic distortion (THD), almost unity power factor, high power density and good efficiency. This rectifier has good steady state performance and fast transient response when operated with voltage oriented control strategy along with PI controller.

17. Dual Inverter Drive

Dual Inverter drive is been operated along with three phase Current Source Converter (CSC) topology. This charger system consists of a three phase LC filter, CSC, dual-inverter, an wound permanent magnet synchronous motor (PMSM) and two energy storage units [29]. This drives allows high voltage drive operation and also compatible to work as a single inverter in case of component failure. Dual inverter [30] has very small current ripples operates at a high frequency, thus small grid LC filters are used. Here the CSC charging system can be bypassed for integrated fast dc charging. CSC based integrated charges utilises EV drive train components like motor windings and drive inverters for charging purpose. The system can charge at high power directly from three phase grid, this reduces a comparative hardware requirement for charging station. Low power single phase ac charging is also commendable by connecting the single-phase grid terminals to two of the three phase inputs in the presented charger

III. Conclusion

This paper reviews performance of DC-DC converter topologies for battery driven electric vehicles and plug in hybrid electric vehicles and converter topologies for fast charging station (FCHAR's). this review focuses on various performance parameters such as component count, switching frequency, use of electromagnetic interference filters, losses, cost and reliability which impacts the selection of converters for a particular application. This review paper also reflects that bridgeless and interleaved converters are better option compared to diode bridge rectifier based converters because DBR have poor efficiency and low power density.

Zero voltage switching converters and converters with resonant circuits are more suitable for low power BEV's and PHEV's as they have smooth starting, soft switching, low EMI, less switching loss and higher efficiency. In case of fast chargers Multiphase AC-DC converters, Vienna rectifier and a Dual Inverter can be opted due to its high power factor, high output current harmonic dissolution applications. In case of DC-Dc stage Three port DC-DC converters, and multiple interleaved buck converter shows better response due to high efficiency, simple control technique and design process. Finally the research which is been carried out and advancement of wide band gap switches (WBGS's) technology converters are getting significant improvement in power density, cost and durability. Also WBGS's reduces switching losses at high switching frequencies to improve overall system efficiency, thus new generation of compact PE converters shows an improvement in efficiency and reliability.

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